Quantifying Warehouse Automation and Sustainability

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ABSTRACT

Beginning in 2020, the e-commerce grocery retail industry grew rapidly, largely due to the COVID-19 pandemic. In addition to this shift in consumer shopping preferences, retailers are facing another challenge: a looming labor shortage. This shortage of workers has caused enormous disruptions across the supply chain, particularly for activities performed within warehouses and fulfillment centers. To tackle these challenges, companies are embracing a series of strategies to help ease the pressure of the labor shortage in warehouses. One of these leading strategies is automation. At the same time, the energy consumption of automation equipment raises concerns of its environmental impact among investors, regulators, and customers alike. Although there are general greenhouse gas accounting standards, there is no comprehensive link between warehouse automation and emissions.

This research proposes a framework for measuring greenhouse gas emissions stemming from warehouse automation. The result is a dynamic carbon emissions calculator that determines the total CO_2 emissions derived from the energy consumption of various automation technologies. The framework is validated using real data from an e-commerce grocery retailer and provides results indicating that sustainability and automation are not mutually exclusive.

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Table of Contents

List of Figures

1. Introduction

1.1. Motivation Statement

The e-commerce grocery retail industry has faced several hurdles in recent years that have complicated their supply chains. One that has become especially apparent is the switch in grocery shopping habits from in-store brick and mortar to online retail channels. Gallup's annual Consumption Habits survey found that in 2019, only 19% of consumers had bought groceries online (Jones and Kashanchi, 2019), whereas by 2020 over 79% of consumers had ordered online, largely driven by implications surrounding the COVID-19 pandemic (Inmar, 2020). By June 2020, total online grocery sales totaled $7.2B compared to $1.2B in August 2019 (Morgan, 2020). This switch in shopping has challenged retailers to reassess their current supply chains and invest in omni-channel fulfillment strategies in order to optimize their networks and best serve customers.

In addition to a shift in shopping preferences, retailers are facing another challenge that has been exacerbated by pandemic related complications: a looming labor shortage. This shortage in workers has caused enormous disruptions in multiple aspects of the supply chain, from manufacturing to transportation to warehousing. In a warehousing context, as individual online purchasing increases, so do the types of activities performed within the warehouse, and more specifically within fulfillment centers. Rather than dedicating labor to moving and shipping pallets of products, companies now have to manage the picking, packing, and shipping of individual orders, which is much more labor intensive (Garland, 2020). This shift in labor requirements, in an environment where there are already pandemic related constraints such as capacity reductions and social distancing requirements, is putting grocery retailers in a difficult position.

In order to tackle these challenges, companies are embracing a series of strategies to help ease the pressure of the labor shortage in warehouses. One of these strategies is automation (Custodio & Machado, 2020). While automation has been a hot topic within supply chains for years, the need for automation has never been greater. The 2021 MHI (Material Handling Industry of

America) annual industry report highlighted the importance of warehouse automation in response to the pandemic. According to the MHI, 52% of companies have seen either increasing or substantially increasing investment in robotics and automation, with the top use for automation revolving around warehouse movements (MHI, 2021).

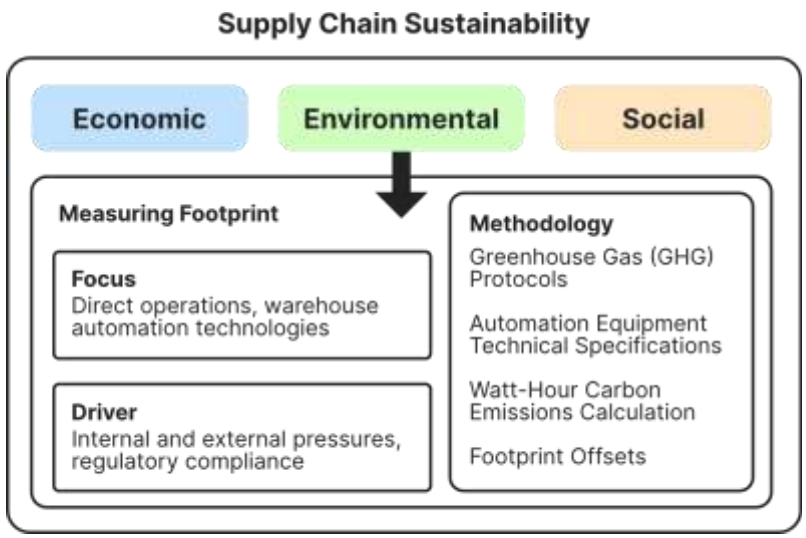
While warehousing automation may seem to be the way of the future, companies must consider how this technology intersects with other objectives within supply chains. Sustainability is a major trend within supply chains that has become increasingly important. According to the UN Global Compact Supply Chain Guide for Continuous Improvement, supply chain sustainability refers to “the management of environmental, social and economic impacts and the encouragement of good governance practices, throughout the life cycles of goods and services” (Sisco, Chorn and Pruzan-Jorgensen, 2015). As of 2021, 60% of companies now have a focus on making their supply chains more sustainable (Unruh, 2020). Over 201 companies, including powerhouse retailers like Amazon, P&G, & HP have signed the climate pledge, committing to net carbon zero by 2040 (AP News, 2021). With an increased focus on sustainability, companies must understand how their adoption of disruptive technologies such as warehouse automation interact with their sustainability goals.

1.2. Problem Statement

The main goal of this project is to quantify the environmental impact of warehouse automation. This study will explore the relationship between warehouse automation and sustainability through three objectives. The first objective is to identify best practices for warehouse automation for omnichannel fulfillment in the grocery retailer space for standalone fulfillment centers. The second objective is to understand how the implementation of warehouse automation can impact the environment; in order to assess the environmental impact this study will assess best practices for comprehensively measuring emissions. Lastly, once the relationship between automation and sustainability has been established, the third objective is to determine what strategies can be implemented to help companies balance their automation and sustainability goals. Figure 1 conceptualizes our framework for addressing this problem.

Figure 1

Conceptional Framework for Automation and Sustainability in Supply Chain



1.3. Hypothesis

We theorize that full end-to-end automation in standalone fulfillment centers will reduce the environmental impact in terms of carbon emissions. The technology required for full automation has matured enough that companies no longer have to make significant investments in its research and development. As such, the adoption of this technology will only become more essential as consumer behavior continues to accelerate toward same-day delivery. Although costs are outside the scope of this project, we also recognize the long-term investment benefits of automation as well as the potential limitations of this technology.

2. Literature Review

As the e-commerce retail market continues to grow, companies must assess current fulfillment strategies to understand how they can best serve their customers. This study analyzes how warehouse automation can be employed to balance challenges associated with growing ecommerce needs, while assessing the environmental impact of this increased automation within e-commerce fulfillment centers. While there is limited research on the topic of sustainable warehouse automation within the grocery retail space, there is abundant research on e-commerce network design in the grocery sector, warehouse automation, and green warehousing; this literature review will be focused as such. These topics overlap, creating a picture as to how ecommerce fulfillment, warehouse automation, and sustainability interact.

2.1. E-Commerce Fulfillment for Grocery Retailers

As e-commerce continues to grow, it is important to understand the design strategy and considerations for ecommerce fulfillment networks. The emergence of omnichannel fulfillment strategies has allowed companies to integrate brick and mortar and online fulfillment to jointly manage inventory across channels, allowing for greater flexibility and demand driven inventory allocation (Wollenburg et al., 2018). However, integrated fulfillment does not come without challenges, as integration has implications on operations, network design, and warehouse activities such as picking, packing and shipping (Kembro, Norrman, Eriksson, 2019).

When determining a strategy to fulfill online demand, companies can employ a combination of different models including in store, ‘dark stores’, online stand-alone fulfillment centers, or most recently micro-fulfillment centers (Eriksson, Norrman and Kembro, 2019; Michel, 2020).

In store fulfillment models utilize existing in store inventory and resources to fulfill orders originating online in a number of hours that are then either delivered to the customer or picked up at the store (Taylor, Brockhaus, Knemeyer & Murphy, 2019). While inventory sharing between online and in store orders can be attractive, in store fulfillment of online orders can deplete in-store inventory, leading to potential loss of in-store sales (Taylor, Brockhaus, Knemeyer & Murphy, 2019). Unlike in store fulfillment, dark stores are facilities with no in store shopping whose purpose is to serve online demand only, with a “concentration of consumers and non-automated stores offering pick up” (Michel, 2020).

Stand-alone FCs are large, dedicated facilities for handing online orders (Marchet et al. 2018). Many retailers in the grocery sector have chosen to adopt dedicated ecommerce FCs because of the differences that occur when fulfilling an online order versus a replenishment order; order lines, order volume, handling units and customer requirements can vary greatly between these two types of orders, and as a result, it is often more efficient to manage fulfillment separately (Eriksson, Norrman and Kembro, 2019). It is important to note that stand alone FCs differ from traditional DCs in that they only fulfill online orders; this distinction is important as stand-alone FCs must be configured to optimize efficient picking of individual items, which means they are often times built from new, vs being repurposed from existing facilities within the network (Eriksson, Norrman and Kembro, 2019).

Micro-fulfillment refers to the use of automated order-picking systems at the local level to fill customer orders for home delivery or store pick-up faster than a traditional ecommerce fulfillment center, and with less labor than in-store fulfillment (Michel, 2020). Trends in online grocery shopping have increased substantially, in part due to the covid-19 pandemic, and the idea behind micro-fulfillment centers is to leverage automation to create more efficient points for fulfillment close to the customer, which can be achieved through varying degrees of automated solutions (Michel, 2020).

Benefits and drawbacks of each model depend on the type and volume of customers being served – whether that be home delivery, click and collect, or in store (Marchet et al. 2018). For example, while utilizing in-store inventories to fulfill online demand for home delivery can be a convenient strategy, store layouts are not designed for picking efficiency, thereby resulting in longer pick times (Hübner, Kuhn and Johannes Wollenburg, 2016), when compared to fulfillment via a stand-alone FC that has been designed to optimize picking efficiency for online orders.

2.2. Warehouse Automation for Fulfillment Centers

As the need to fill online orders accelerates, many retailers are looking for ways to more efficiently manage order fulfillment networks. Traditional methods of manual order processing are being replaced by AI robotics to limit the number of steps taken by warehouse workers, and even complete tasks that were previously thought to only be capable of being executed by human workers (Caulfield, 2019). According to the 2020 Industrial Automation report, the industrial automation market is projected to be valued at $352B by 2024 (Transparency Market Research, 2020), despite 80% of warehouses still operating entirely manually as of 2019 (Warehouse Automation: Rise of Warehouse Robots, 2019). While automation does require extensive investments, there are several benefits that occur from streamlining flows and reducing costs; factors driving automation include increased sorting and packaging, higher utilization of space capacity in the warehouse, and increased ergonomics and safety (Kembro & Norrman, 2019).

While automation within warehouses is expected to drive increased efficiencies, there are several drawbacks, most notably the lack of flexibility (Kembro & Norrman, 2019). This lack of flexibility contrasts with omnichannel retailing, as it is generally characterized as having larger product assortments and variations (Kembro & Norrman, 2019). Regardless of drawbacks, many retailers continue to explore automated solutions for end to end warehousing activities.

Receiving, stowage, picking, packing, and shipping are key activities that occur within warehouses, and the decision to automate these processes can have a huge impact on warehouse design and configuration (Eriksson, Norrman and Kembro, 2019). The decision to automate activities, and to what degree, as well as the type of facility being automated will determine what type of automated solutions that can be employed (Hubner, Kuhn, Wollenburg, 2016).

In this study we will be reviewing end to end solutions with varying levels of automation that can be employed in stand-alone FCs to automate the following five principal activities: receiving, stowage, picking, packing, and shipping. Through our own market research we have identified eleven types of technologies that relate to these activities including automated truck loading system, depalletizers, decanters, sortation systems, automated storage and retrieval systems, person to goods picking, goods to person picking, robotic picking, packout systems, conveyors and automated guided vehicles (AGV's) or also commonly referred to as automatic mobile robots (AMRs). These technologies can be combined to create semi-automated and fully automated warehouse solutions.

Figure 2

Categorization of Automation Technologies

	Semi-Automated	Automated
Receiving		ATLS, Depalletizers, Decantors, Sortation
Stowage		AS/RS
Picking	Person to Goods, Goods to Person	Robotic Picking
Packing & Staging	Packout System	AGVs, AMR, Conveyors

For the purpose of this study, we define a fully automated solution as one that requires minimal human intervention, such as robotic picking arms, and a semi-automated solution as one that requires some level of human input, like goods to person picking. Visual examples of the technologies described below can be found in Appendix A.

2.2.1. Receiving

In the warehousing process, receiving typically refers to the act of inbound flow of material. Goods must be received accurately, and sorted quickly, which is why many companies have their most tenured employees managing the receiving process (Kembro, Norrman, Eriksson, 2019). From an automation perspective, the types of technology related to receiving include automated truck loading systems, depalletizers, decanters, and sortation systems.

The primary receiving activity includes unloading products from the transport carrier (Custodio & Machado, 2020). Automated truck loading systems (ATLS) are an automatic truck loading and unloading system refers for the insertion and removal of pallets into or out of a truck with little to no operator intervention, reducing a task that typically takes 30 minutes to under 10 minutes (Automatic truck loading and unloading systems, 2021). While not as widely used as other types of automation, ATLS are becoming popularized as companies such as Interlake Mecalux, Honeywell, and Ancra.

Once pallets are unloaded, each must be depalletized and case packs decanted. This refers to taking items in mixed case packs, breaking down the packs, and then removing individual SKUs that will then be sorted through a sortation center and deposited in an automated storage and retrieval system (AS/RS). Palletizing robotics systems exist to help receive and ship material in and out of the warehouse, with an increasing emphasis on considerations for product weight, size and fragility (Warehouse Automation: Rise of Warehouse Robots, 2019). PlusOne Robotics, Mujin, and TCW all manufacture these types of solutions. Once items are depalletized, they are then moved to the decanting stations, where boxes are weighed, opened and individual items are removed from the box. Conveyco's Automated Case Cutting and Decanting System can decant up to 800 cases per hour, helping to eliminate the second most labor activity in the warehouse (Automatic Case Cutting and Decanting Goods to Person and Replenishment System, 2021). Once items are properly decanted, they can then be sorted.

According to LogisticsIQ, automated sorting is already widely adopted: These systems are used to sort items in to be stored in an AS/RS system, or for parcels out of the warehouse conveyor system before shipping (Warehouse Automation: Rise of Warehouse Robots, 2019). Companies currently producing sortation solutions include CASi's CASI-Sort, Berkshire Gray's Robotic Shuttle Sortation, and Bastian's Tompkins t-sort.

2.2.2. Stowage

In traditional fulfillment centers, stowage usually includes forklifts and racking systems to put away, store, and retrieve material. Put away and storage accounts for approximately 15% of labor in a warehouse (Correl, 2021). Automated Storage and Retrieval Systems (AS/RSs) are warehousing systems that are used for the automated storage and retrieval of products for the order picking process, which typically utilize racks, cranes, or automated vehicles to move pallets, without input from a human operator (Roodbergen & Vis, 2008). AS/RS is typically the most complex portion of automation, and includes automated racking, shelving and shuttle systems (Warehouse Automation: Rise of Warehouse Robots, 2019).

There are several different types of automated storage solutions, which can be categorized into two categories, stationary and mobile. Stationary systems utilize fixed racking systems and AMRs or robotic cranes to pick cartons containing eaches and then deliver that to a workstation via a conveyor system. Mobile solutions involve non-fixed racks that can be transported directly to the workstation via an AMR. There are many solutions providers in this space, with over 26 members in the Material Handling International Automated Storage/Retrieval Systems (AS/RS) Industry Group, including AutoStore, TGW & Ocado (MHI, 2021).

Similar to AS/RS, autonomous vehicle storage and retrieval systems (AVS/RS) utilize automated guided vehicles (AGVs), or driverless vehicles that are equipped with an automatic guidance system, and are programmed to follow a specific path, moving pallets and containers throughout the warehouse. (Custodio & Machado, 2020). AGVs are more flexible than fixed conveyor systems as they can be reprogrammed to adjust for changes in pathway operations and less labor intensive than typical modes of warehouse transportation, such as forklifts as they remove the need for human operators, offering a safer, more predictable method for managing pallets without the need of human interference (Custodio & Machado, 2020).

2.2.3. Picking

Perhaps one of the highest priority activities for automation is order picking and packing due to its heavy manual labor requirements within the warehouse (Custodio & Machado, 2020), and as a result has derived several types of solutions with varying automation. Picking an order may involve a warehouse employee walking through rows of products to find individual items for an order. Many solutions have been introduced to increase picks per hour; we explored picking three strategies: person to goods, goods to person, and robotic picking. Aside from storage systems, the picking system solution space is perhaps the most saturated in terms of available technology.

Person to goods picking is the most traditional form of automation picking technology and involves the picker moving to a stationary location to pick goods and place them in a tote. Pick carts, which direct pickers on which items to pick via a display screen, allow pickers to pick multiple orders at once. Handheld devices that direct pickers are also a common form of technology (MMCI Distribution, 2022).

Automatic retrieval of items for goods to person picking or robotic picking is typically incorporated in AS/RS systems that are described in the above system through the use of pick ports. Automatic retrieval systems deliver specific SKUs to a workstation where items are then picked manually or robotically.

Goods that are delivered to a workstation and then picked manually are referred to as goods to person systems. Goods to persons systems utilize software systems that guide the picker through the order, directing the picker to transfer designated items to an order container (Warehouse Automation: Rise of Warehouse Robots, 2019). Systems can detect picking errors and alert the picker to correct them before the picker can continue with the order. Oftentimes these workstations are built ergonomically to promote workplace safety and ensure pickers avoid injury

(Workstations & Piece Picking Robot - Workstations for Warehouse Automation, 2021). Manufactures in the G2P and robotic picking space include Swisslog's CarryPick (Swisslog, 2021) and TGW's PickCenter One (Workstations & Piece Picking Robot - Workstations for Warehouse Automation, 2020).

Robotic picking solutions are becoming more robust with the introduction of 'soft manipulation' that allows more fragile objects to be picked directly from the shelf to the packaging and shipping corner of the warehouse (Warehouse Automation: Rise of Warehouse Robots, 2019). These are fully automated solutions that require almost no human interaction as a robotic arm is capable of moving the object through a grasping mechanism. Right Hand Robotics manufactures robotic picking arms that uses an intelligent gripper, vision system and AI to leverage machine learning for better hand eye coordination (Right Hand Robotics, 2021). Similarly, Swisslog's ItemPiQ has 4 unique grasping techniques that can pick an assortment of goods, which is integral in the grocery space (Swisslog 2021). Dematic, another competitor in this space, has robotic piece picking solution that claims to operate 24/7 with 99.99% accuracy and fast pick rates of up to 600–1200 items/hr. (Dematic 2021).

2.2.4. Packing and Staging

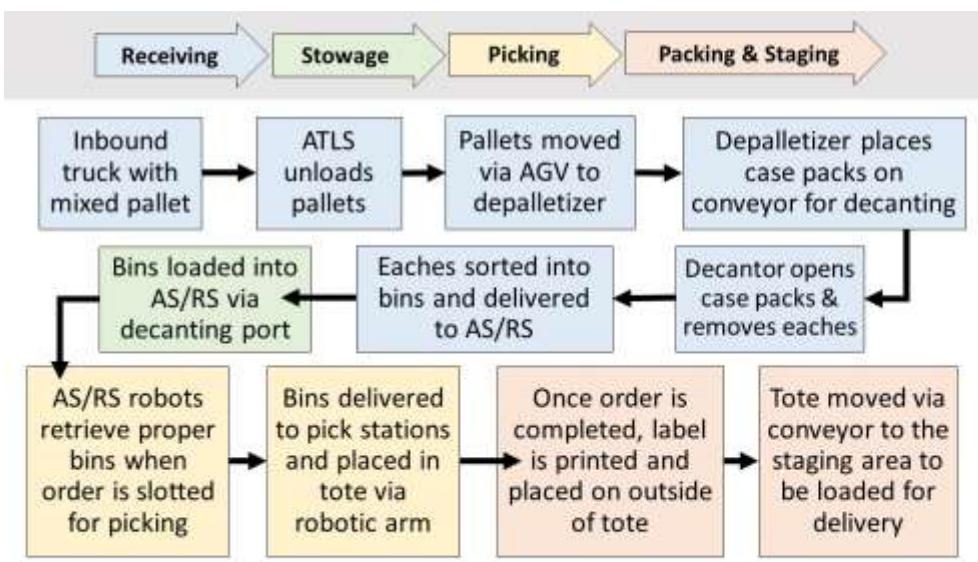
Once items are picked, they are moved to the packing and shipping stage (Custodio & Machado, 2020). Generally packaging refers to any final labeling or boxing. Once labeled, orders are moved to the staging portion of the warehouse, where they are then shipped depending on preferred mode designated by the retailers. 6 River systems packout system utilize stations where finished orders are scanned and then labels are printed to be added prior to the final destination (6 River Systems, 2021).

Once orders are packed, they need to be moved to a staging area to be loaded onto vehicles for final delivery. AMRs or AGVs, which are cited as some of the most useful types of technology due to their flexibility (Custodio & Machado, 2020), can then be used to deliver finalized orders to the staging area for shipping. Dating back over 100 years, conveyor belt systems are the more traditional method for transporting materials throughout a warehouse and between warehousing activities. It is worth noting that according to a paper published by Material Handling International, conveying equipment can consume up to 50% of a facility's energy usage (Insight Automation, 2022).

The end-to-end material flow for an automated warehouse facility is illustrated in Figure 3. It is important to note that this is just one example of an automated facility. Any of the below automated activities could be completed manually, and as few or as many technologies can be combined to achieve the desired level of automation.

Figure 3

Material Flow in an Automated Warehouse



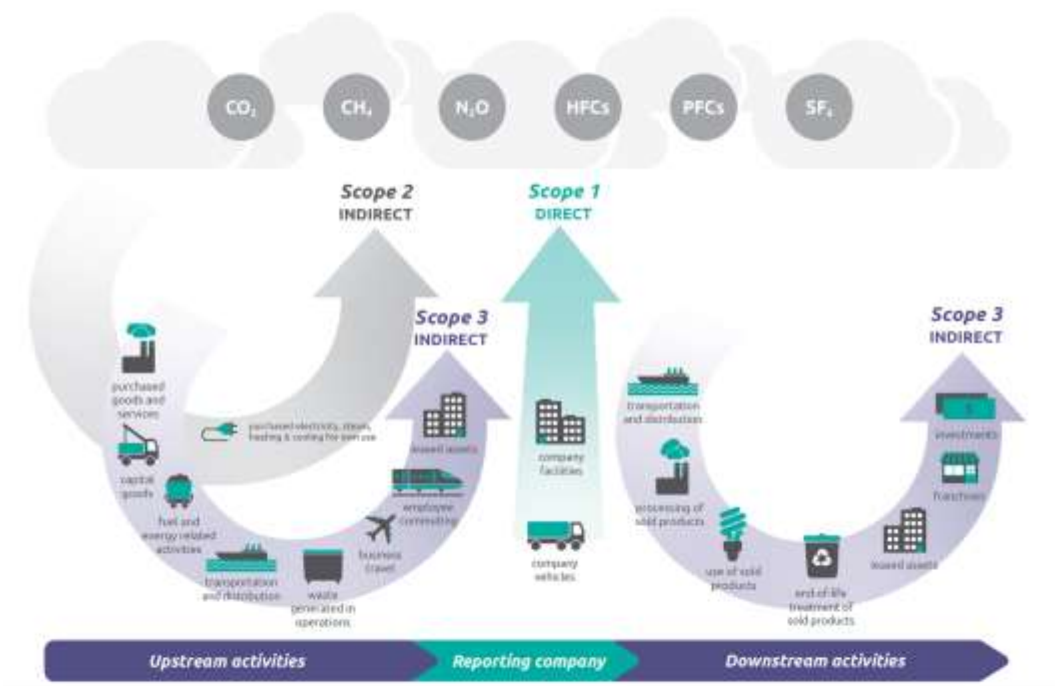
2.3. Sustainability Frameworks

Greater awareness and responsibility for "sustainability" has dramatically increased in corporate operations in past decades (Cory Searcy, 2014), yet there is no universal agreement on its precise definition. The United Nations first defined sustainability at the Brundtland Commission as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (United Nations, 1987). Within the supply chain discipline, Kumar et al. (2014) proposed the notion of “green supply chain management” as the relationship between operational efficiency and environmental performance. Moreover, “green warehousing” has appeared in narrow literature focused on activities including inventory management (Gu et al., 2010), order fulfillment (Mishra et al., 2011), optimal space utilization (Topan and Bayindir, 2012), operational efficiency (Yang et al., 2012), loading/unloading problems (Fichtinger et al., 2015), and material handling (Reaidy et al., 2015). For the purpose of this research, we refer to sustainability as the environmental and ecological scope, but not social, economic, regulatory, or other forms of sustainability.

Quantifying the impacts of environmental sustainability relies heavily on the chosen methodology. There are numerous frameworks developed for measuring the impacts of environmental sustainability, but no single approach has been globally adopted. Among the most common tools include the Task Force on Climate-related Financial Disclosures (TCFD), the Global Reporting Initiative (GRI), and the United Nations Global Compact (UNGC). The Greenhouse Gas Protocols (GHGP), which is now the most widely adopted framework for reporting GHG emissions (World Resource Institute), provides accounting and reporting standards, sector guidance, calculation tools, and training for corporations. This framework breaks down emissions into three main categories: Scope 1, Scope 2, and Scope 3 as illustrated in Figure 4. Scope 1 derives from sources in direct control or ownership by the company, such as vehicle fleet in the context of supply chain. Scope 2 emissions are indirect emissions associated with the purchase of electricity, including heating or cooling. Although Scope 2 emissions are not typically generated at the warehouses, we consider them as part of the overall emissions calculation as a result of the warehouse’s energy consumption, particularly in automation equipment and machinery. Scope 3 emissions are the activities stemming from assets not owned or controlled by the reporting company, but nonetheless impacts its supply chain. Although we do not consider Scope 3 emissions from automation equipment, we do consider the carbon output tradeoff between labor and automation when evaluating our results.

Figure 4

Greenhouse Gas Protocol Scopes



Note. Adapted from U.S. Environmental Protection Agency, 2022.

2.4. Greenhouse Gas Emissions

The largest contributor of greenhouse gas emissions in warehouses is by far energy, as researched extensively in past literature including Bartolini, Bottani, and Grosse (2019), Abeydeera, Mesthrige, and Samarasinghalage (2019), and Boenzi et al. (2015), among others. Carbon emissions caused by material handling activities within warehouses account for a significant 13% share of overall supply chain emissions (World Economic Forum, 2009). However, past literature on the environmental impact of warehouses is limited, with Dhooma and Baker (2012) and Fichtinger et al. (2015) being notable exceptions.

Fichtinger et al. (2015) showed how "the systematic assessment of carbon emissions caused by warehousing activities is based on a set of parameters and aggregates, determining overall energy consumption that is translated into carbon dioxide emissions". As such, our methodology considers overall warehouse floor space (including multi-level buildings) as direct inputs into energy consumption for heating, ventilation and air conditioning (HVAC), lighting, and material handling equipment (MHE), as proposed in Ries et al. (2017). Our research considers how automated material handling equipment for the five principle warehousing activities impacts the throughput level and energy consumption of such systems.

When considering the construction of warehouses, Rai, Sodagar, Fieldson, and Hu (2011) studied the operational carbon emissions of these activities. The location of these facilities is an indirect but also significant form of energy consumption, according to Szczepanski et al. (2019). The warehouses' position on the power grid and subsequent energy sources from renewables or non-renewable fuels is considered as part of the emissions calculation.

2.5. Linking Automation and Sustainability

In recent years, automated storage and retrieval systems (AS/RS) have had a considerable impact in sustainability (MHIA 2009). Meneghetti and Monti (2015) proposed how AS/RS enables inventory to be stored more compactly than traditional warehouses. Their model reduces the energy used to cool, light, and ventilate excess square footage. Furthermore, the advantage of vertical space allows storage of the same number of units in a smaller footprint, thereby requiring fewer resources including concrete and reducing overall carbon dioxide emissions. Finally, Makris, Makri, and Provatidis (2006) consider the correlation between service time and energy consumption in warehouse operations, and conclude automation may lead to a significant decrease in energy consumption.

Perhaps the most relevant literature comes from Tappia et al. (2015), who investigated the trade-offs between the energy consumption and the environmental impact of automated warehousing systems using real data. Their conclusion revealed that autonomous vehicle storage and retrieval system (AVS/ RS) performs better than automated storage and retrieval system (AS/RS) from an environmental perspective due to its greater energy efficiency per cycle, whereas Lerher, Edl, and Rosi (2014) concluded that energy consumption and carbon dioxide emissions increase with greater velocity of AS/RS.

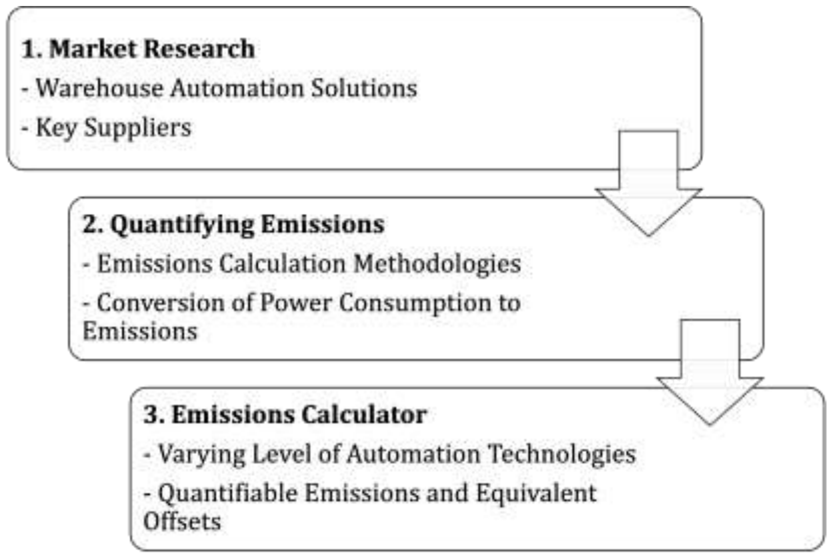
3. Data and Methodology

The objective of this study was to understand the environmental impact of warehouse automation in standalone e-commerce fulfillment centers within the grocery retailer space. Through our literature review, we determined that although there is significant research on e-commerce fulfillment network design, warehouse automation, and sustainable warehousing, there are few papers examining the intersection of these three topics.

In order to answer this question, we split our analysis into three sections with different methodologies that culminated in a quantitative analysis of warehouse automation and its environmental implications (Figure 5). First, we conducted market research on the types of warehouse automation solutions available today, and what are the key companies manufacturing these technologies. Next, we reviewed the methods in which environmental impact can be measured and quantified within the warehouse setting for e-commerce fulfillment. Lastly, we created an emissions calculator and matrix summarizing types of automation for warehouse activities with varying levels of manual labor and the quantifiable environmental impact of each activity and labor level. We then compared this matrix to solutions currently being utilized at non-automated e-commerce facilities and automated FCs within the sponsoring company's e-commerce fulfillment network.

Figure 5

Research Methodology Overview



3.1. Warehouse Automation Solutions Market Research

The sponsor company currently operates a variety of fulfillment centers within their supply chain network, with varying levels of automation. Most recently they have invested in automation for their large standalone fulfillment centers that serve their ecommerce channels. In order to understand all available options for FCs managing similar volume and order sizes, rather than focusing on the automation solutions currently being employed, we conducted market research on what solutions currently exist and which companies are players in this space. We also reviewed past Request for Proposals (RFPs), as well as spoke with representatives at partnering companies and toured automation facilities.

3.2. Emissions Qualifications & Measurement

As outlined in the literature review, we applied Greenhouse Gas Protocols, or GHG (World Resource Institute), which continues to be the world's most widely used emissions accounting standards. The GHG Protocol Corporate Accounting and Reporting Standard provides requirements and guidance for companies preparing GHG emissions inventory, which we tied based on level of warehouse automation. This standard covers the seven greenhouse gasses under the United Nations Kyoto Protocol: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PCFs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). However, the emissions derived from automation equipment is primarily CO_2, and therefore the focus of this study.

To calculate emissions, we reviewed a number of open source cross-sector calculation tools made available by the Greenhouse Gas Protocols, in addition to sector-specific methodologies used within the grocery retailer space, in order to create our own calculator. We then used energy consumption data provided by manufacturers' technical specifications, as well as real data from the sponsor company to create a comprehensive calculation for automation emissions (Figure 6).

Figure 6

Emissions Calculator for Facility A Sample Data

Calculator	Options
Automation Level:	Full
Warehouse Size:	Medium (500K SQFT)
Energy Source:	Petroleum/Gas (50/50%)

Annual Total	
kW/Year	235,411
kgCO2/Year	170,650
Trees Offset	7,838
KM Driven	1,420,902

Receiving

Technology	Model	kW/Hour	gCO2/Hour	Units	Use/Day	Per Day	Hours	Days	kW/Year	kgCO2/Year
Decant Stations (Dry)	Swisslog Port Conveyor 5.1 N-BA-DDG	0.040	27.58	8	100%	8	2	350	224	154.44
Decant Stations (Chill)	Swisslog Port Conveyor 5.1 N-BA-DDG	0.040	27.58	6	100%	6	2	350	168	115.83

Picking

Technology	Model	kW/Hour	gCO2/Hour	Units	Use/Day	Per Day	Hours	Days	kW/Year	kgCO2/Year
Automated Pick Carts	Cannon Equipment Propick Picking Cart	1.224	843.90	15	70%	11	1	350	4498	4430
Relay Pick Ports (Dry)	Relay Port Touch 220 1.0	0.050	34.47	3	100%	3	8	350	420	290
Relay Pick Ports (Chill)	Relay Port Touch 220 1.0	0.050	34.47	2	100%	2	8	350	280	193
Assisted Picking	Zebra TC52 Wireless Handheld	0.015	10.34	20	70%	14	1	350	74	72
									0	0

As defined in the GHG protocol, we focused on Scope 1 and Scope 2 emissions but excluded Scope 3. Scope 1 refers to the direct emissions produced from corporate activities, such as on-site fossil fuel combustion and fleet fuel consumption. Specific to warehouses in the retail grocery space, this includes real estate footprint. Scope 2 refers to emissions from purchased or acquired electricity, steam, heat and cooling. This scope is critical when determining the level of electricity in warehouse automation. Scope 3 includes categories within the value or supply chains of the company's activities, including purchased goods and services, transportation and distribution, and use of sold products. This would also refer to energy generated by WMS systems for advanced computing and data processing. We determined these factors to be out of scope for our research as stated in the motivation.

To calculate emissions, we found the least common denominator among all automation equipment to be the watt-hour. This universal unit of energy is the rate at which electrical work is performed when a current of one ampere (A) flows across an electrical potential difference of one volt (V). As such, if watt-hour was unavailable in the technical specifications, a simple conversion from volt-amperes was performed (1W = 1V * 1A). Using the operating hours data from the sponsor company, we estimated the total number of hours in a standard year that the equipment would be powered at average output. Multiplying these estimates to the watt-hour per equipment gives the total watt consumption in such a given year, which is then reduced to a more logical kilowatt unit of measure. Formulaically:

$$\frac{X_W \times X_H \times D}{1{,}000} = \; kW/Year$$

where X is the automation equipment, W is the watt-hour consumption, H is the hours operational in a standard day, and D the number of days the warehouse is operational in a given year.

Emissions are derived from the power grid region and energy source, including coal, petroleum oil, natural gas, renewables (without distinction to solar, wind, or other renewables), and a mix of all four sources. In its simplest form, we calculated emissions using the U.S. average for petroleum oil at 2.3 pounds of CO_2 per kilowatt (U.S. Energy Information Administration). We convert this number to kilograms to maintain consistency with the International System of Units

(SI), which results in 1.03 kg CO_2. As such, our total kW/Year consumption from the above formula is then multiplied by 1.03 kg to determine the total kilograms of carbon dioxide emissions.

Applying this methodology for different automation equipment, and thereby different levels of automation, provides a reasonable estimate of CO_2 emissions per facility in a given year.

4. Results and Analysis

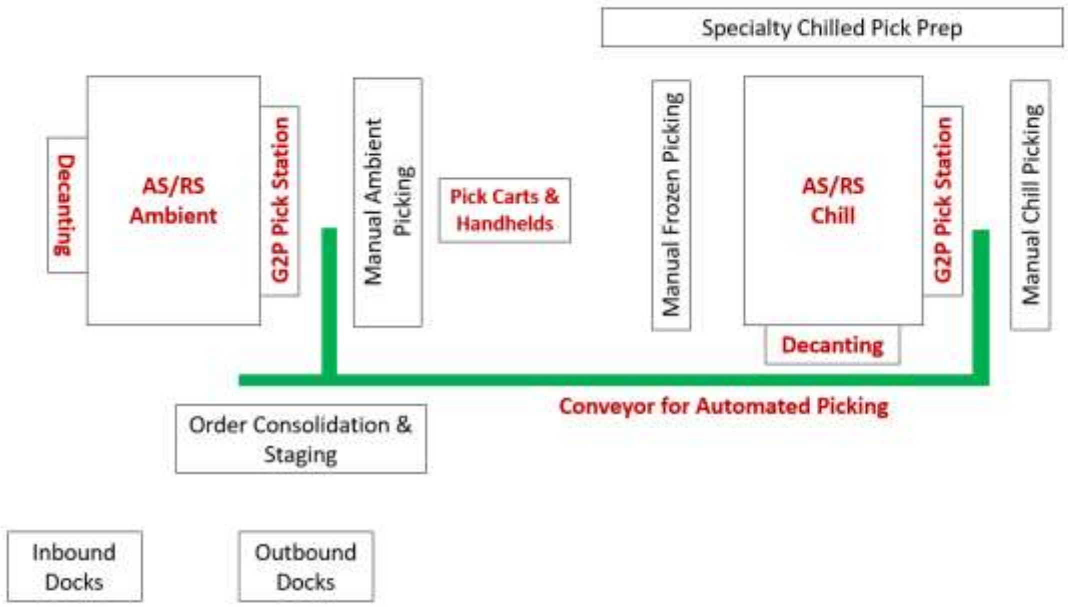
In this chapter we will discuss the results of our research, including the emissions calculations and efficiency comparison, provide commentary on the impact of energy sources, explain the limitations of our research, and comment on potential alternative methodologies.

4.1. Results

To analyze the relationship between automation and sustainability, we created a carbon emissions calculator that took inputs from the sponsor company, calculated total energy expenditure, and then converted this energy usage into CO_2 emissions. For our primary analysis, we reviewed automation levels at Facility A. According to our sponsor company, Facility A is their most automated e-commerce fulfillment center, boasting technologies such as decanting stations, AS/RS systems, automated pick carts, G2P pick ports, assisted picking via handhelds and conveyor belts, as detailed in Figure 7.

Figure 7

Facility A Warehouse Automation Layout

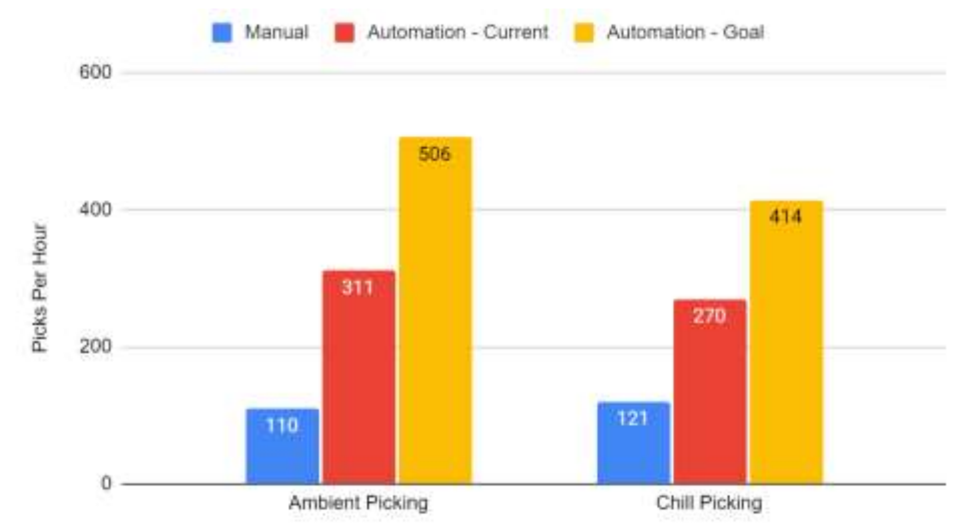


From our analysis, we estimated that Facility A produces 170 metric tons (MT) of CO_2 per year in relation to their automation technology. For perspective, in order to offset this level of emissions, the sponsor company would need to plant over 7,000 trees. However, reviewing estimated emissions by technology revealed that some types of automation are much more energy intensive than other types of technology. For example, assuming that the sponsor company uses motorized roller conveyors, at an estimated 140 MT of CO_2 per year, the energy intensity of the +1,000ft conveyor system far surpasses that of any other automation, making it the worst technology from an energy intensity perspective. Conversely, the decanter ports emit less than .02 MT of CO_2 per year. Because conveyor technology is commonplace in most warehouses, when this type of technology is excluded from the calculator, the estimated emissions from automated technology drops to 30 MT of CO_2 per year.

One may argue that any increase in emissions due to automation is automatically detrimental from an environmental perspective. However, an increase in automation directly reduces labor. Figure 8 details the relationship between pick rates and automation level. The chart demonstrates that as automation increases, pick rates also increase. Automated ambient picking is approximately 4x more effective than manual ambient picking, and automated chill picking is 3x more effective than manual chill picking. When considering the efficiency gains of automation for just picking alone, a warehouse would need an additional 7 employees a day to maintain the same pick rate. Each employee will have an additional carbon footprint, such as the emissions generated from commuting to the warehouse. As such, the tradeoff between automation instead of manual labor may be less impactful to the environment.

Figure 8

Pick Rates at Sponsor Company by Automation Level



To analyze the positive impact of efficiency gains from automation, we first calculated labor reductions in the number of employees, made possible by efficiency gains in automation. To do this, we reviewed the throughput rates of the ambient and chill picking for Facility A. We determined that in order to achieve the same throughput achieved through automation, Facility A would need to employ 7 additional employees: 4 additional employees for ambient picking and 3 for chill picking, as illustrated in Figure 8. These 7 additional employees would generate an estimated 43 MT of CO_2 per year simply by commuting 55 minutes to work each day compared to the 30MT of

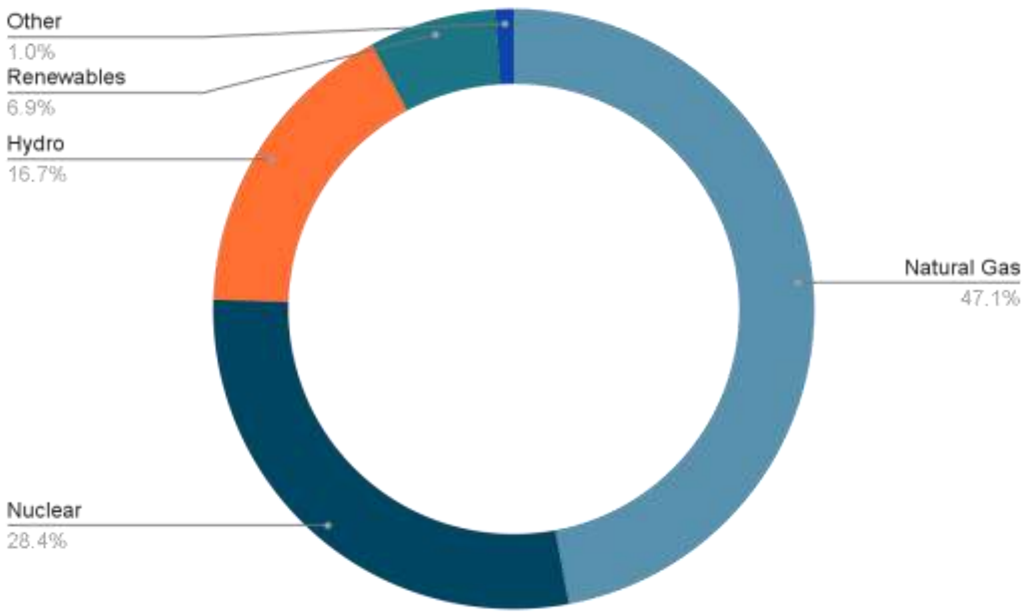
CO_2 generated by the core automation technology (when excluding the conveyor belt). From this analysis, we have determined that when considering efficiency gains, automation is a sustainable option for ecommerce fulfillment.

It is important to note one limitation with this methodology of comparison. For this analysis we compare Scope 1 and Scope 2 emissions generated from the automation with the emissions generated from employees commuting to work, which are categorized as Scope 3 emissions. Although the comparison of energy from automation (Scope 2) and emissions generated from a commute (Scope 3) are not a direct comparison in the type of emissions, we believed it was the most appropriate comparison as we needed to incorporate the efficiency gains into the analysis, as labor shortage is the primary motivator behind automating activities.

In addition to the emissions calculations, through this process, we determined that the greatest external factor for greenhouse gas emissions stemming from automation equipment is the energy source powering the equipment. Our research found that coal fuel is the heaviest emitter of carbon dioxide at 1,011.511 grams per kilowatt hour. In contrast, renewables such as hydro, nuclear, solar, and wind produce the fewest emissions in the range of 5 to 50 gCO_2 per kilowatt hour (National Renewable Energy Laboratory, 2013). Note that renewable does not necessarily mean zero emissions, as some greenhouse byproducts are still produced. To estimate automation emissions more precisely, the energy source of the warehouse must be considered. For instance, Figure 9 demonstrates a breakdown of fuel sources for one of the sponsor company's warehouses in the New England grid.

Figure 9

Fuel Mix for Sponsor Company Warehouse



Using the breakdown of these energy sources, we developed a formula for total CO_2 emissions for the automation equipment using a mix of different sources. In essence, we attribute an emissions factor and weight for each fuel source, the sum of which provides the total CO_2 emissions per watt hour. For instance, if we assume the fuel mix portfolio of Figure 9, the total emissions is 223 grams of CO_2 per kilowatt hour. This formula is incorporated into the emissions calculator and dynamically updates based on the level of automation. As described in Chapter 3, we rely on a combination of EPA and EEA emissions factors for all of the main renewable and non-renewable sources.

4.2. Limitations

Perhaps the largest limitation of this model, and future analysis, is the difficulty in collecting the appropriate data sources. Many types of automation do not readily list the energy usage per hour, or any mention of energy usage. As discovered during our market research, some manufacturers will make claims about low energy usage, or improvements in efficiency, without providing any statistics to back these claims. To find this information, we had to work with the sponsor company to contact representatives at the manufacturing companies or make assumptions on energy estimations based on pre-existing literature.

In relation to the fuel source, note that the fuel mix may vary by month, week, and even hour. Whereas solar and wind energy would be the dominant sources of energy in a typical day, it could be natural gas or petroleum oil that overtake as peak producers during climate conditions unsuitable for solar panels or windmills. Our research assumed a stable fuel mix based on the data provided by the sponsor company.

Another material factor to consider with automation equipment is the computing power and related energy consumption. Some of the more advanced automation systems, such as AS/RS, will require computers with servers and related semiconductors to perform the calculations that enable the automation algorithms to run. As with the fuel mix, the equipment will also impact the emissions derived from this computing power.

Lastly, this calculation was strictly related to automated activities. This model did include any emissions related to other energy expending activities within a grocery fulfillment center, such as lighting, air conditioning, refrigeration, etc. Although outside the scope of our analysis, the introduction of automation within a facility could have an impact on the amount of energy used for lighting, refrigeration, air conditioning etc.

4.3. Alternative Methodology

Our methodology for sustainability focused on the environmental aspect, specifically Scope 1 and Scope 2 emissions per the Greenhouse Gas Protocols. An alternative methodology for calculating sustainability would have been to include Scope 3 emissions. This scope would consider the emissions arising from the supply chain related to the automation equipment itself, including the raw materials processing (e.g., lithium and nickel for the batteries), manufacturing (e.g., factory lighting, heating, and cooling), logistics and installation (e.g., freight from factory to end customer warehouse), and even decommissioning (e.g., waste produced from recycling or remanufacturing). Furthermore, Scope 3 emissions could have considered the carbon offset of automation equipment in relation to a manual labor force. For instance, if an automated warehouse reduced or eliminated the use of a human labor force, the related savings in commuting emissions via public or private transport could be considered as an offset in total emissions. Likewise, if the automation equipment reduced the physical footprint of land area for warehouse facilities by consolidating area and enabling greater vertical operations, that as well would be considered an offset.

5. Discussion

From the inception of this project, we faced several roadblocks that would ultimately shape the final deliverables of this capstone. Some of the roadblocks involved narrowing the scope of the project: e-commerce fulfillment models vary greatly, for example, when considering a micro-fulfilment center versus a standalone fulfillment center versus a dark store.

Additionally, while we were able to research different types of automation technology, it is difficult to suggest which manufacturer produces the 'best' automation technology because solutions are incredibly personalized and the end goals of the business must be taken into account. Factors such as level of integration, desired flexibility, willingness to invest, future network strategy, and price sensitivity all play an integral role when determining what level of technology is best for a business, aside from looking at the emissions impact alone.

Furthermore, one of the biggest roadblocks we faced was access to data and information regarding automation technology. Initially, our intention was to create a matrix that would compare automation emissions for each warehouse activity (receiving, stowage, picking, packing, and staging) by the level of automation (fully automated, semi-automated, no automation). We realized that without information directly from our sponsor, it would be difficult to create a matrix with this level of detail because information surrounding kWh for different types of technology, and throughput rates for specific activities, like manual decanting or sortation, is scarcely publicly available. In order to gather this information, we would likely need to do an independent study of three warehouses within the sponsor's network, with three different levels of automation, which is beyond the scope of this project.

Lastly, although this research does not make specific recommendations for warehouse automation outside the context of environmental sustainability, it is important to consider the consequences of employing such technologies. A reduced workforce would be expected as more robotics replace traditional human-performed functions.

6. Conclusion

Through this research, we have proposed and verified a framework to quantify the impact of sustainability when implementing automation in omnichannel fulfillment in the grocery industry, with considerations to efficiency gains made through automation. This research will help inform companies on how their automation strategies impact sustainability goals, and provides insights on how companies can continue to reduce emissions within their warehouses.

Our research showed that Facility A, through the use of decanting stations, AS/RS systems, automated pick carts, relay pick ports, assisted picking and conveyor belts, would save 13MT of CO_2 emissions per year, while employing 7 fewer humans to run the facility, when compared to a facility of the same size and throughput that does not use the core automation technology. Based on our findings, we offer several insights regarding management recommendations as well as avenues for future research.

6.1. Insights and Management Recommendations

6.1.1. Measuring Sustainability of Automation Framework

The primary framework for this calculation is fairly simple, yet required many tweaks to create a model that was easy enough to implement given the data constraints, and one that provided a link between automation efficiency and sustainability.

For our model we determined that following inputs to be the most important when calculating emissions: energy type, type of automation (automation model), kWh per type of automation, 'units' of automation (e.g., the number of decanting stations), hours per day in operation, days per year in operation, percent utilized during operational hours, and emissions factors. We found that these data points could be captured by the company, and created a comprehensive calculation for estimating the CO_2 emissions from each type of technology. Once we created our emissions calculator, we needed to determine a strategy for linking emissions from automation to automation efficiency vs sustainability. We determined that the best method to compare efficiency gains and sustainability would be to compare the emissions generated from the commutes of the 'additional labor needed' for a manual model to achieve the efficiency of an automated facility, to the emissions generated from the automation technology which we derived using our calculator.

We found that this was the most digestible way to link efficiency gains to emissions. If the emissions generated from employees commuting to work is greater than the emissions generated by automation to achieve the same level of throughput as manual labor, then automation is a more sustainable option.

While this framework does create a connection between automation, sustainability, and efficiency, it is important to note that this is not a comprehensive analysis. As stated throughout the paper, this analysis did not include Scope 3 emissions, nor did it include energy generated from non-automation activities such as lighting, refrigeration, or other energy attentive activities not directly related to automation.

6.1.2. Key Conclusions

Our research confirmed our initial hypothesis that full end-to-end automation in standalone fulfillment centers would reduce the environmental impact in terms of carbon emissions. Specifically, we draw several conclusions on the relationship between automation and sustainability. The primary, and most important conclusion, is that automation and sustainability are not mutually exclusive. When considering the efficiency gains made through automation, automation has a similar level of yearly CO_2 emissions when compared to human labor needed to complete those same activities. Additionally, emissions from automation can be further reduced when seeking out renewable energy sources. In this instance, our sponsor company primarily uses gas and petroleum. By seeking out renewable energy sources, the sponsor company could further reduce the impact of emissions from automation.

Another insight from this project is the importance of data availability, and organizational structure. To gather the data, our primary sponsor had to work through several different organizations before finding the relevant information. By providing a structured system to manage relevant data, our sponsor company could improve reporting and analytics, which will help with future innovation, and reduce the labor hours in which employees spend seeking out information.

Our final insight is that automation technology and sustainability is still a very up and coming industry. While our sponsor company has taken meaningful steps in integrating automation into their facilities, there is still an abundance of solutions available that could further increase the automation and efficiency of their e-commerce warehouses. Specifically in the grocery industry, there are impressive applications being explored for robotic gripping arms for fragile and perishable items that could further reduce manual labor for order picking. Due to the frequent advancements in this industry, the sponsor company must continue to study these advancements to ensure their automation strategy remains relevant.

6.2. Future Research

As noted in prior sections, this research was an introduction to the relationship between automation and sustainability. The following sections describe areas to be studied in future research.

6.2.1. Scope 3 Impact

Our research focused primarily on Scope 1 and Scope 2 emissions. However, to complete a comprehensive analysis of carbon footprint, one must consider implications outside of direct emissions and purchased energy. Scope 3 emissions are typically the most difficult to capture as companies must consider the emissions related to all aspects of the supply chain. In the context of warehouse automation, the most obvious Scope 3 impact is the computational power required to run the warehouse management system for these data intensive technologies. Other types of emissions that would need to be captured would be the energy expended to manufacture, ship, and install this type of automation within a warehouse space.

6.2.2. Social and Economic Implications of Automation

We focused primarily on the environmental aspect of ESG, however, the macro implications of automation extend far beyond just the environment. For example, when implementing automation, the question of whether reducing labor, and therefore reducing jobs is socially ethical. Mercadona, a Spanish grocery store, challenges this perspective noting that the purpose of automation is to automate tasks so that employees can utilized for their unique skills and knowledge, rather than wasting time on tasks that could be done by a machine (Kalloch & Zeynop, 2017). Wal-Mart has adopted this perspective as well, citing that automation eliminates mundane tasks, allowing associates to utilize their creativity and compassion for other responsibilities

(Hanani, 2022). However, critics may argue that the introduction of automation takes away from blue collar jobs. Another social implication of automation is the potential impacts to safety and labor in warehouses (Lui, Joe, et al., 2022). When used correctly and responsibly, automation has the ability to eliminate human involvement from the most dangerous warehouse activities, and improve the working conditions within the warehouse.

6.2.3. What Qualifies as 'Fully Automated'

We explored the concept of a 'fully' automated facility versus a 'semi'-automated facility. Our sponsor company provided data and information to what they have referred to as a 'fully automated' facility, however, several activities within that facility still require manual input, like loading and unloading, decanting, picking, packing and staging. To distinguish semi-automated from fully automated, one must define what a fully automated facility looks like, and whether a truly fully automated facility is even possible. In our research we discovered an abundance of solutions for some activities, like storage and retrieval, but a distinct lack of solutions for other activities, such as packing and loading or unloading. Further research on what qualifies as a truly automated warehouse, and the energy requirements for full automation, would further the discussion on automation and environmental sustainability.

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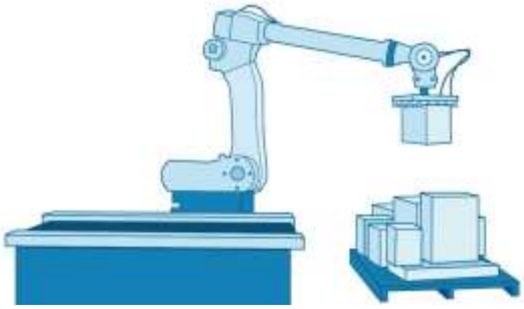
Appendix A: Automation Technology Examples

Source: Interlake Mecalux Automated Loading & Unloading System



Source: PlusOne Robotics Depalletizer

Source: Conveyco Case Cutting and Decanting System

Source: CASi-SORT Automated Receiving

Source: AutoStore AS/RS (in Partnership with Swisslog)

Source: MMCI Distribution Pick Cart

Source: TGW Goods-to-Person Pick Stations

Source: Swisslog ItemPiQ

Source: Six River Systems Packout System

Source: Locust Robots Automated Mobile Robots

Source: TGW Conveyor System